Prospects of Sterile Neutrino Oscillation and CP Violation Searches at SBN

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A quick outline

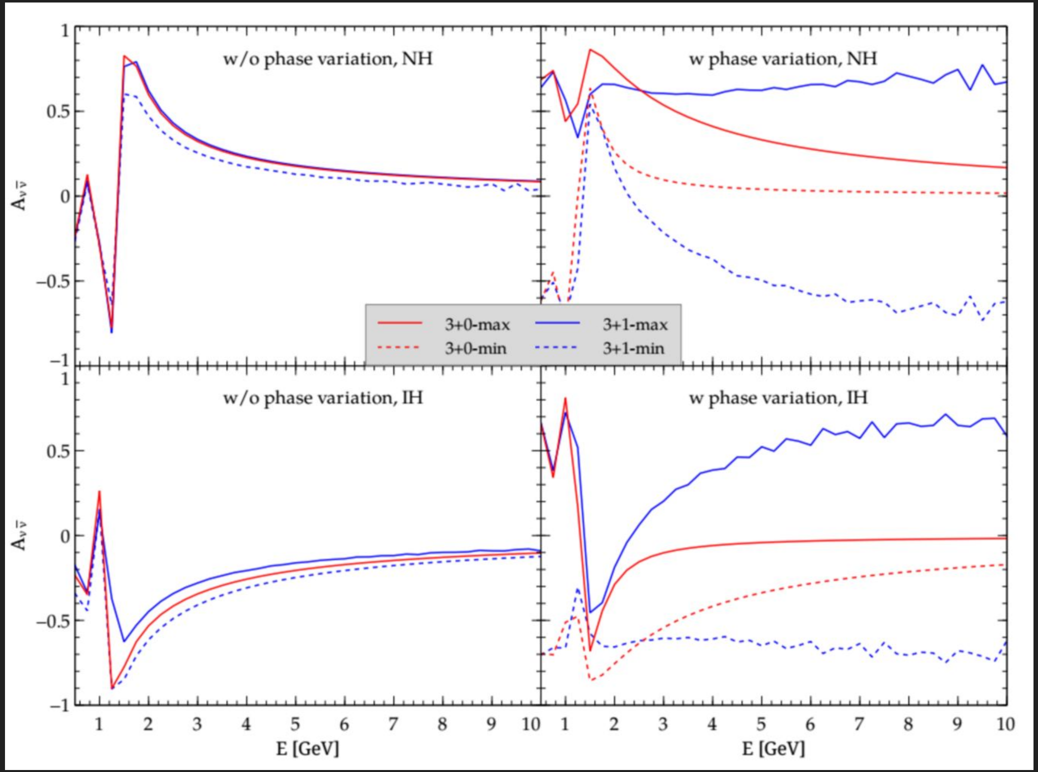
- Why are sterile neutrinos important?
- What are sterile neutrinos in the first place?
- Where are the globally allowed regions to find sterile neutrino oscillation?
- How sensitive will SBN be to those regions of parameter space?
- Will SBN have any sensitivity to additional CP violation phases in the lepton sector?

Why are sterile neutrinos important?

Finding evidence to prove or disprove the existence of sterile neutrinos is critical to studying CP violation in long baseline experiments.

Even a single sterile neutrino can drastically affect sensitivity at long baselines.

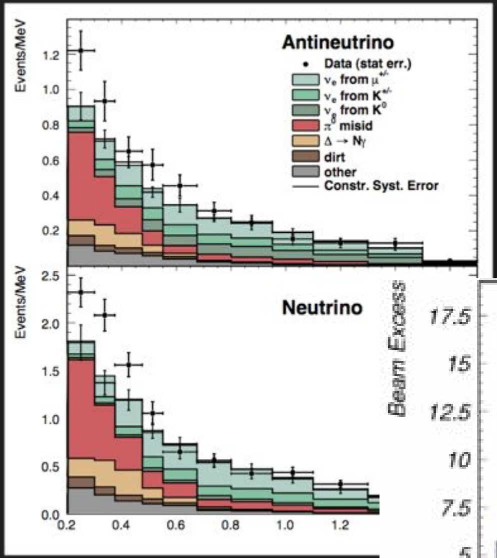
Like in DUNE.



R. Gandhi et al. JHEP 1511 (2015) 039

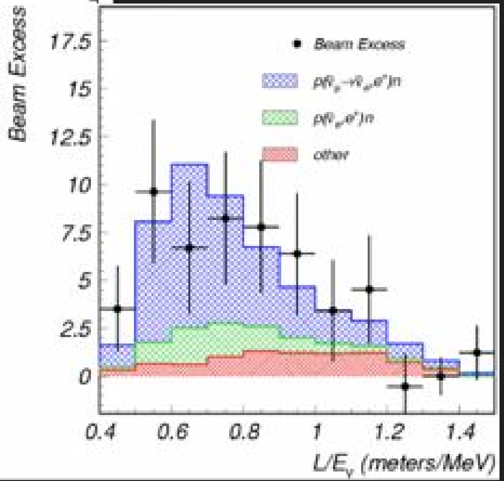
Sterile neutrino hints from short-baseline experiments

MiniBooNE



Phys. Rev. Lett. 110, 161801 (2013)

LSND



Phys. Rev. D 64, 112007 (2001)

Both LSND and MiniBooNE found an excess of electron (anti)neutrinos in a beam of muon (anti)neutrinos.

A possible explanation is that these muon (anti)neutrinos are oscillating through additional, mostly sterile states.

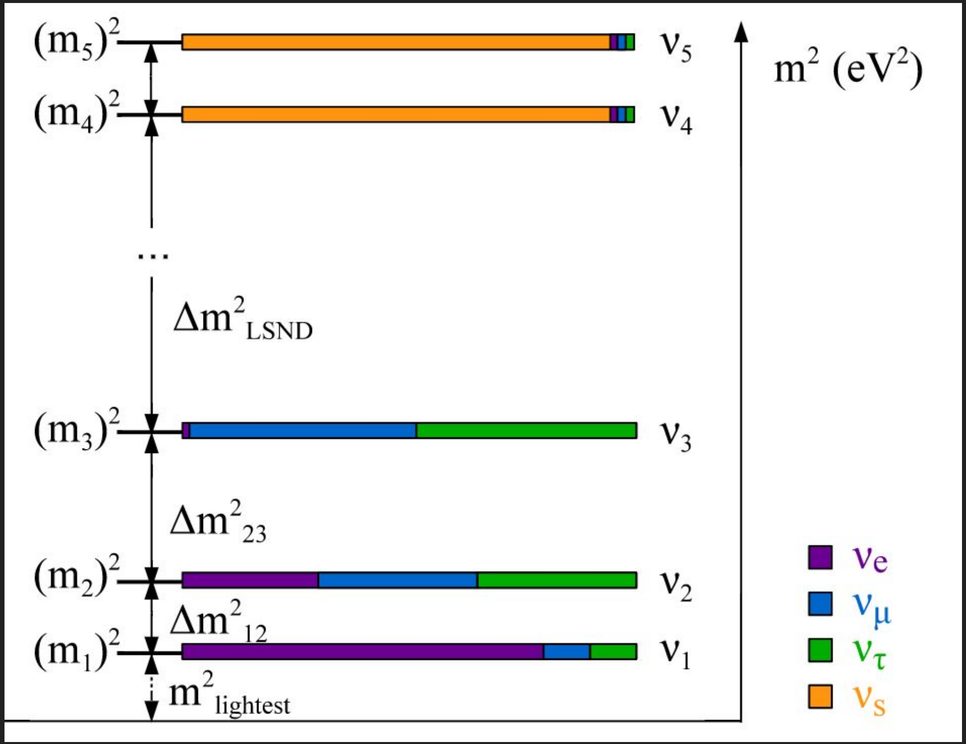
$$\nu_\mu \rightarrow ? \rightarrow \nu_e$$

3 Active + N Sterile (3+N)

Any neutrino flavor exists as a superposition of the three known mass states as well as potential, mostly sterile mass states, the proportions of which can be seen in the relative sizes of the colored bars.

$$|\nu_\alpha\rangle = \sum_{i=0}^{N} U_{\alpha i}|\nu_i\rangle$$

- Δm^2_{41}, Δm^2_{51}
- U_{e4}, $U_{\mu 4}$, U_{e5}, $U_{\mu 5}$
- ϕ_{54}



Here is an example of a 3+2 sterile neutrino model

Global fits

One can assemble a hypothetical oscillation hypothesis assuming some 3+N oscillation and compare it against observed data to see how well it matches.

Global fits are performed following analysis method from Conrad et al (2013)*.

Dataset	Oscillation	ν Channel	Osc. Type
KARMEN	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\bar{\nu}$	App
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN, LSND (xsec)	$\nu_e \rightarrow \nu_e$	ν	Dis
MINOS-CC	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\bar{\nu}$	Dis
MiniBooNE - BNB	$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$	ν, $\bar{\nu}$	App
MiniBooNE/SciBooNE - BNB	$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$	ν, $\bar{\nu}$	Dis
MiniBooNE - NuMI	$\nu_\mu \rightarrow \nu_e$	ν	App
Gallium (GALLEX and SAGE)	$\nu_e \rightarrow \nu_e$	ν	Dis
Bugey	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	$\bar{\nu}$	Dis
CCFR84	$\nu_\mu \rightarrow \nu_\mu$	ν	Dis
CDHS	$\nu_\mu \rightarrow \nu_\mu$	ν	Dis
NOMAD	$\nu_\mu \rightarrow \nu_e$	ν	App

*:Adv.High Energy Phys. 2013 (2013) 163897

Global Fit Results: 3+1

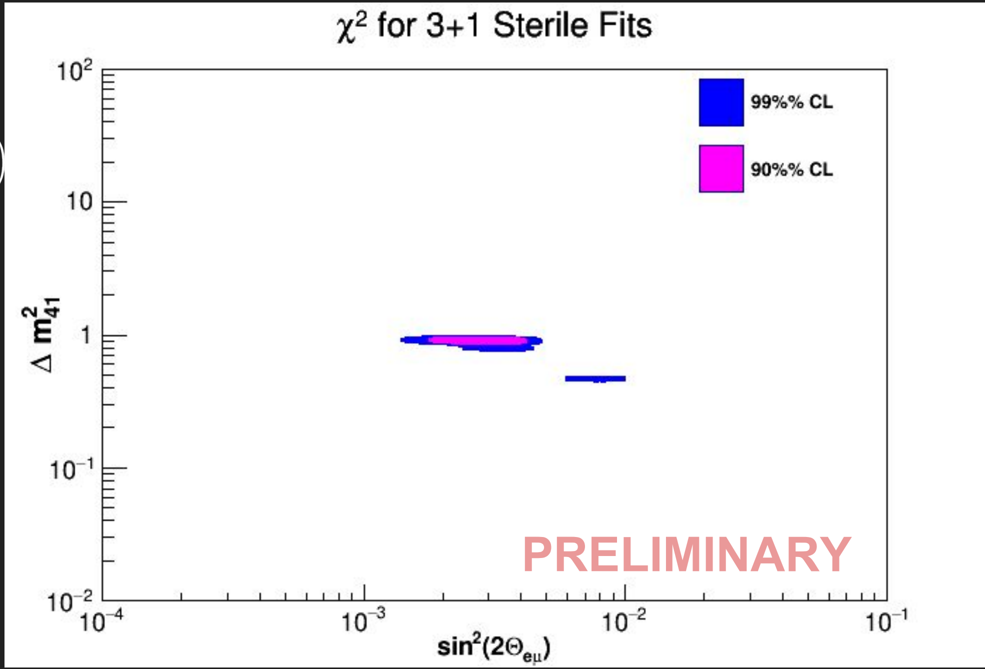
3+1 oscillation probability:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta_{\alpha\beta}) \sin^2(1.27\Delta m^2_{41} L/E)$$

where

$$\sin^2(2\theta_{\alpha\beta}) = 4|U_{e4}|^2|U_{\mu 4}|^2$$

Some global fit studies (Conrad et al, for example) found tension in 3+1 models between different datasets, particularly those of appearance vs. disappearance.

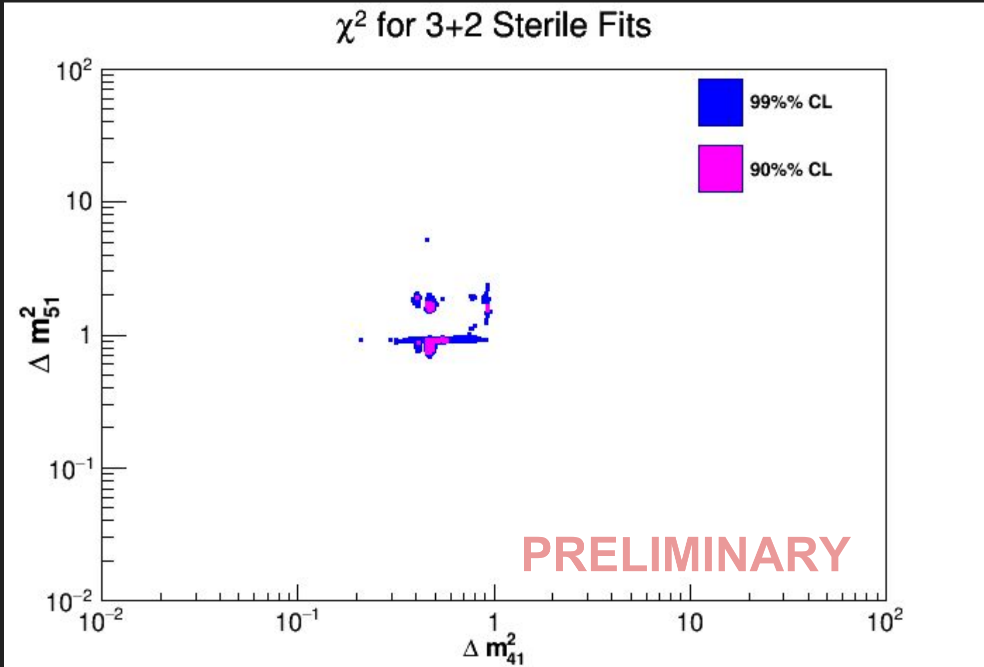


Conrad et al, arXiv:1602.00671 [hep-ph]

Global Fit Results: 3+2

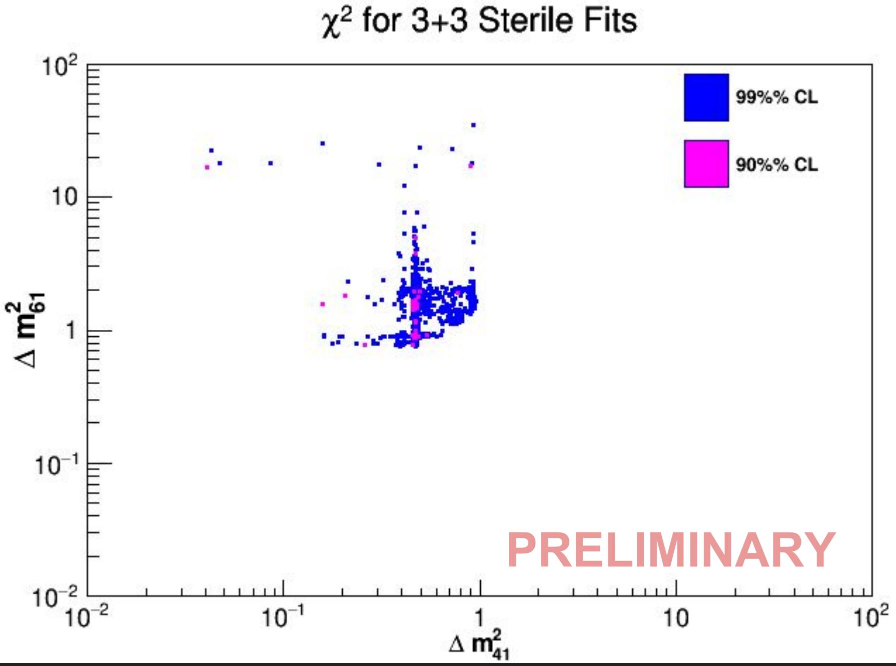
3+2 (and 3+3) oscillations introduce CP violating phases, which can relieve tension between neutrino and antineutrino experiments.

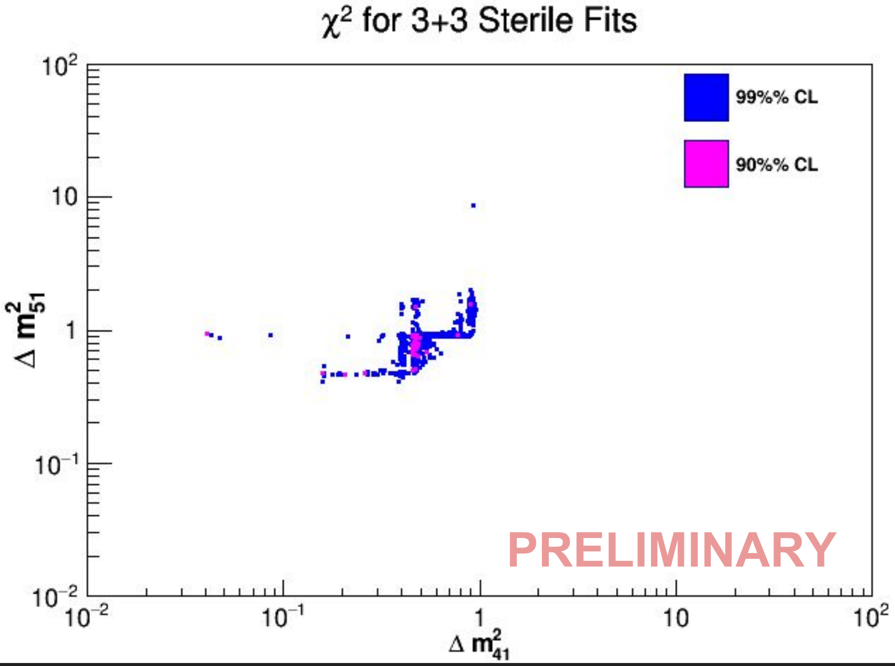
The addition of each new sterile neutrino introduces both new mixing matrix elements and new CP violating phases. The 3+2 model has 7 total parameters and 3+3 has 12.



$\phi_{45} = 287°$

Global Fit Results: 3+3





ϕ_{45} = 287°, ϕ_{45} = 320, ϕ_{45} = 280°

Why Do We Need SBN?

Global fits to 3+N models can be made reasonably well with all datasets to all 3+N models. However, 3+1 models still show some tension between different datasets.

The additional parameters of 3+2 and 3+3 help relieve this tension, but they still fail to adequately reconcile the MiniBooNE low energy excess.

We need a high sensitivity experiment to explore the $\nu_\mu \rightarrow \nu_e$ probabilities suggested by LSND and MiniBooNE at 3+1 as well as 3+2 and 3+3. It is also critical to probe both appearance and disappearance channels.

SBN is well poised to do all of this and more!

The SBN Sensitivity Calculation

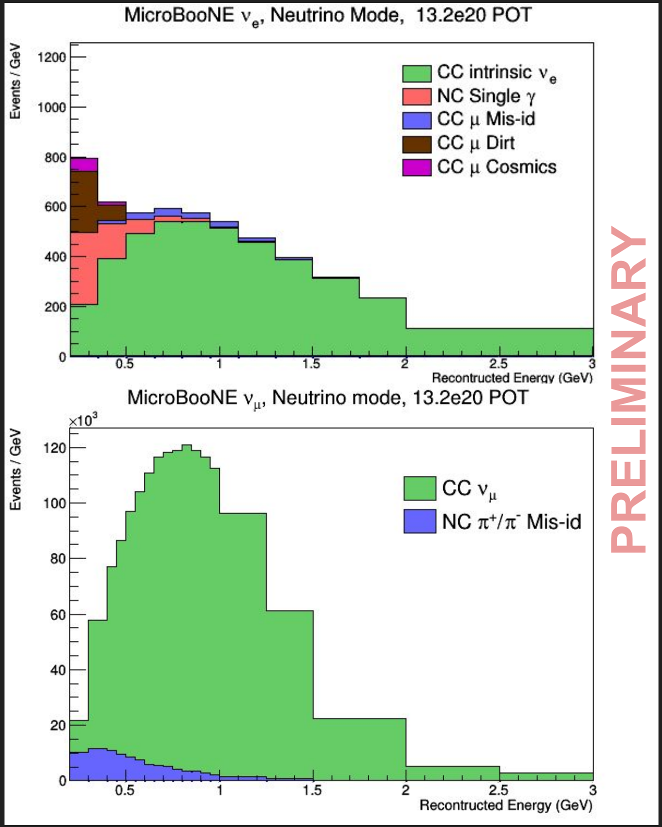
$$\chi^2_{SBN} = \sum_{i,j} (P_i - B_i) M^{-1}_{ij} (P_j - B_j)$$

P_i: predicted event rate assuming sterile neutrino oscillation with some hypothetical set of oscillation parameters.

B_i: background event rate assuming no sterile oscillation, evaluated based on assumptions made in the SBN proposal.

M_{ij}: covariance matrix containing the systematic (flux, cross section, detector) and statistical uncertainties for each detector, as well as systematic correlations.

A Multi-Channel Search



$$\chi^2_{SBN} = \sum_{i,j} (P_i - B_i) M^{-1}_{ij} (P_j - B_j)$$

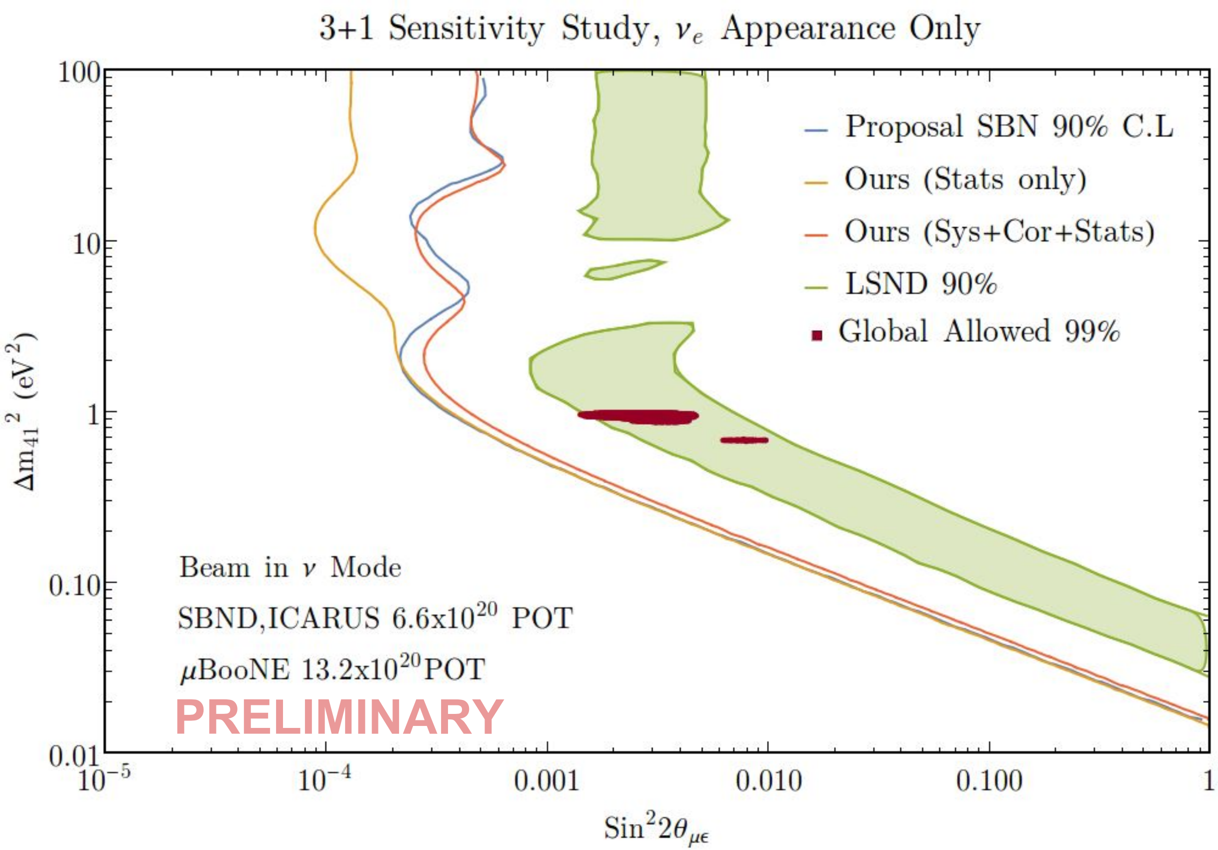
The i and j span over each energy bin for each detector for both ν_μ CC and ν_e CC distributions.

The ν_e CC distribution allows for both ν_e appearance and ν_e background disappearance sensitivity studies. All channels can be fit simultaneously or separately

3+1 Sensitivity in SBN

Event rates are predicted for all three detectors in SBN and used to determine the program's sensitivity to sterile neutrino oscillation

Oscillation parameters are varied and a χ^2 is evaluated for each 3+N model.

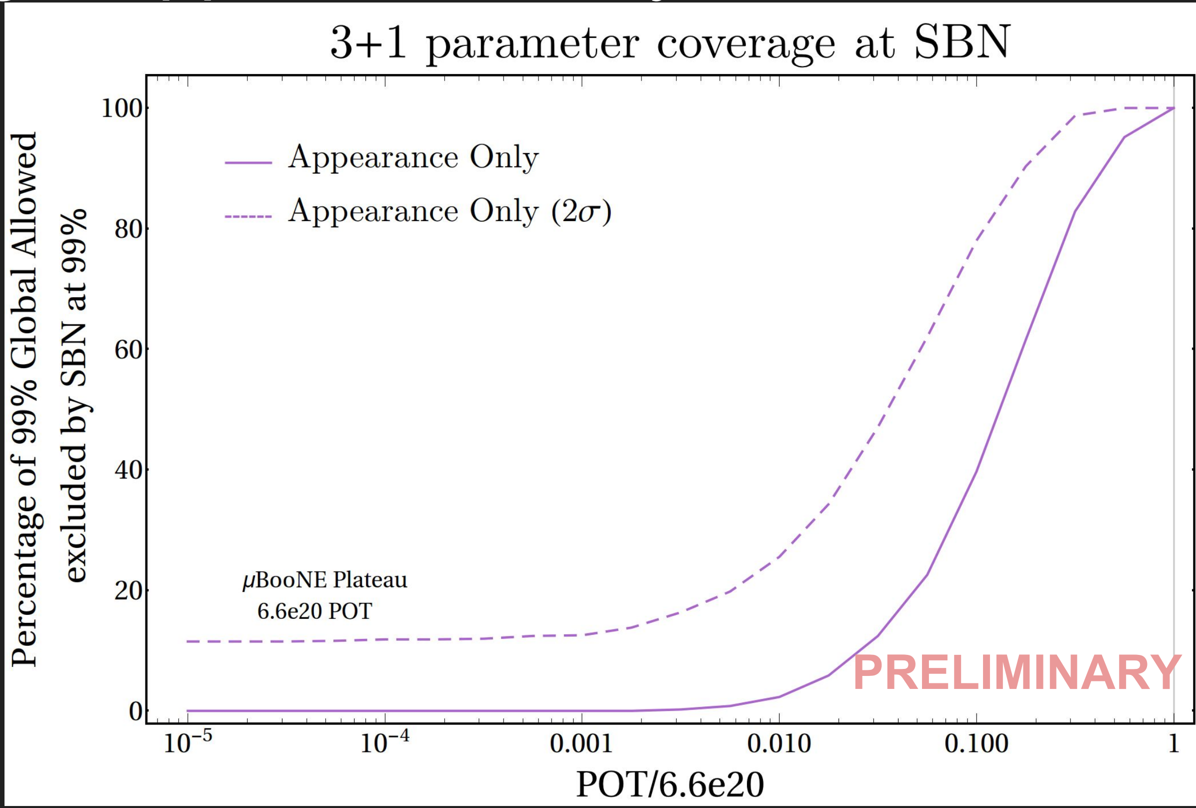


SBN Proposal :arXiv:1503.01520 [physics.ins-det]

3+1 Global Coverage: Appearance Only

This shows how much of the 99% globally allowed region SBN will be sensitive to at 99% confidence.

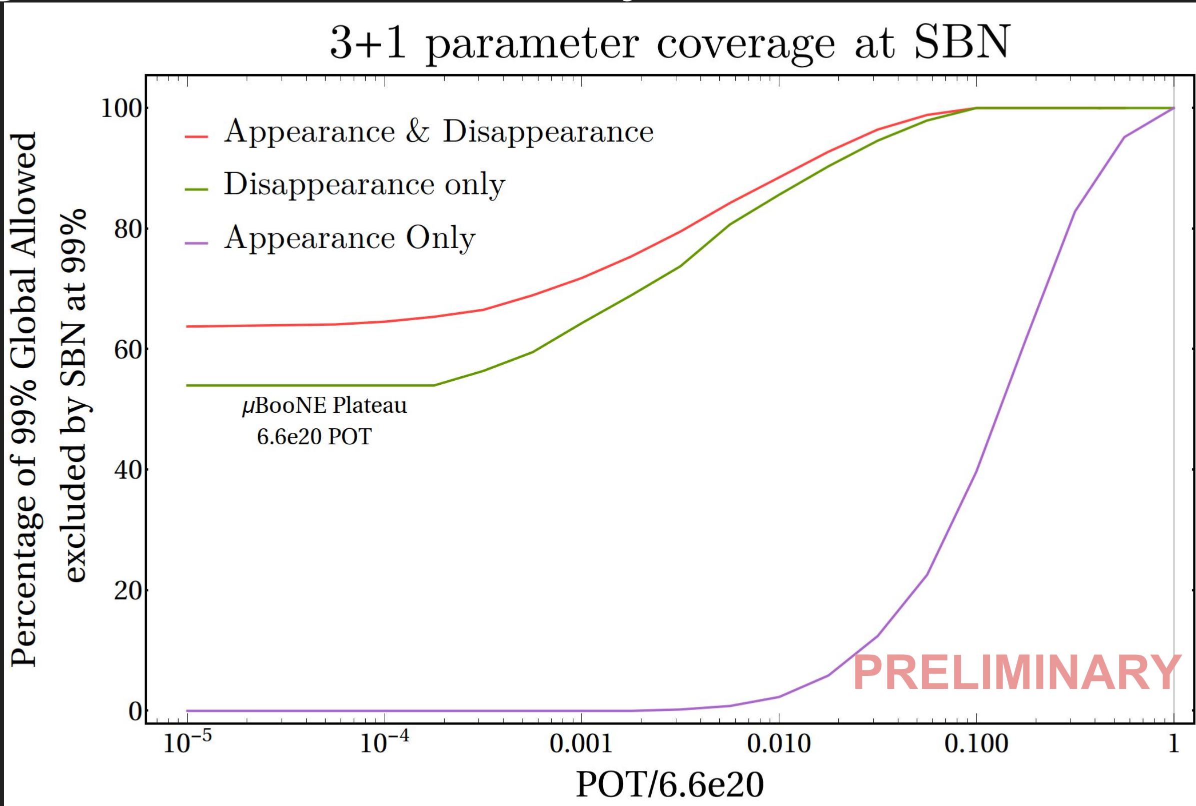
It is drawn with respect to relative POT, starting after MicroBooNE has already received 6.6E20 POT.



3+1 Global Coverage: Combined Analysis

This shows how much of the 99% globally allowed region SBN will be sensitive to at 99% confidence.

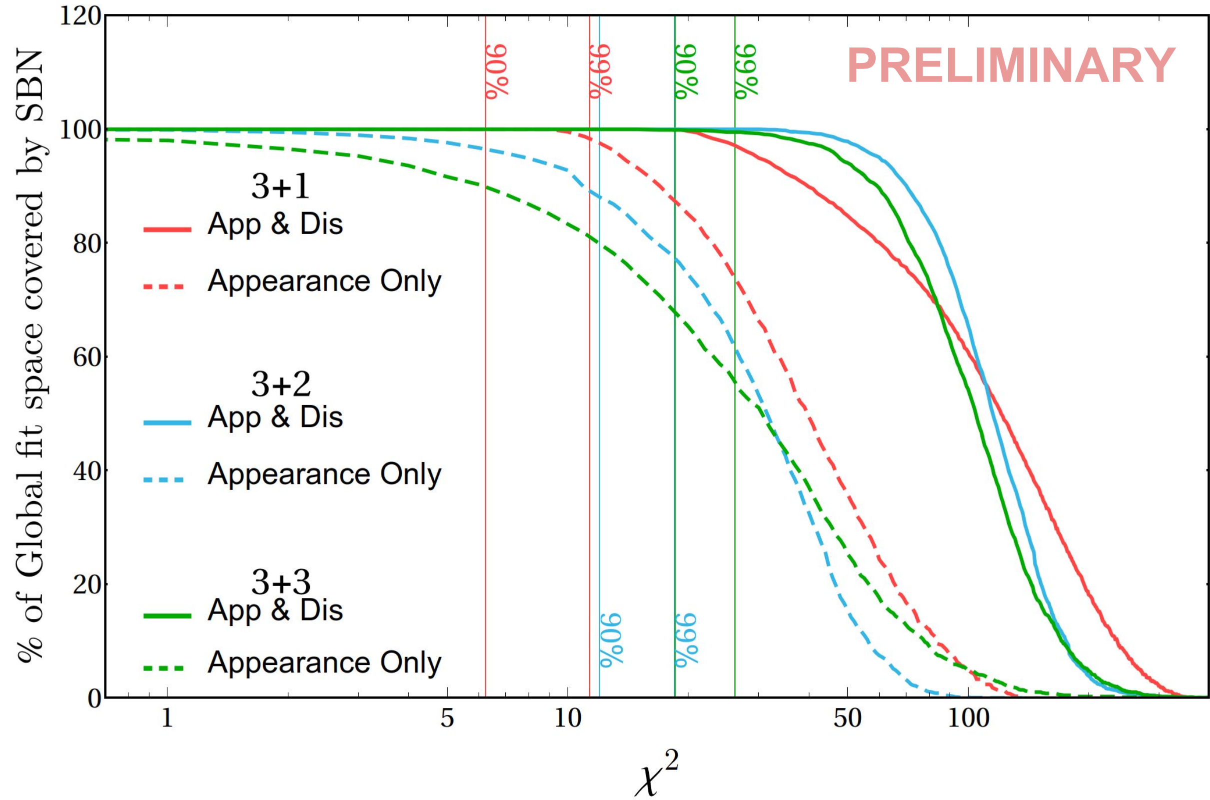
A combined appearance and disappearance analysis can achieve complete coverage of the globally allowed region with only 10% total POT.

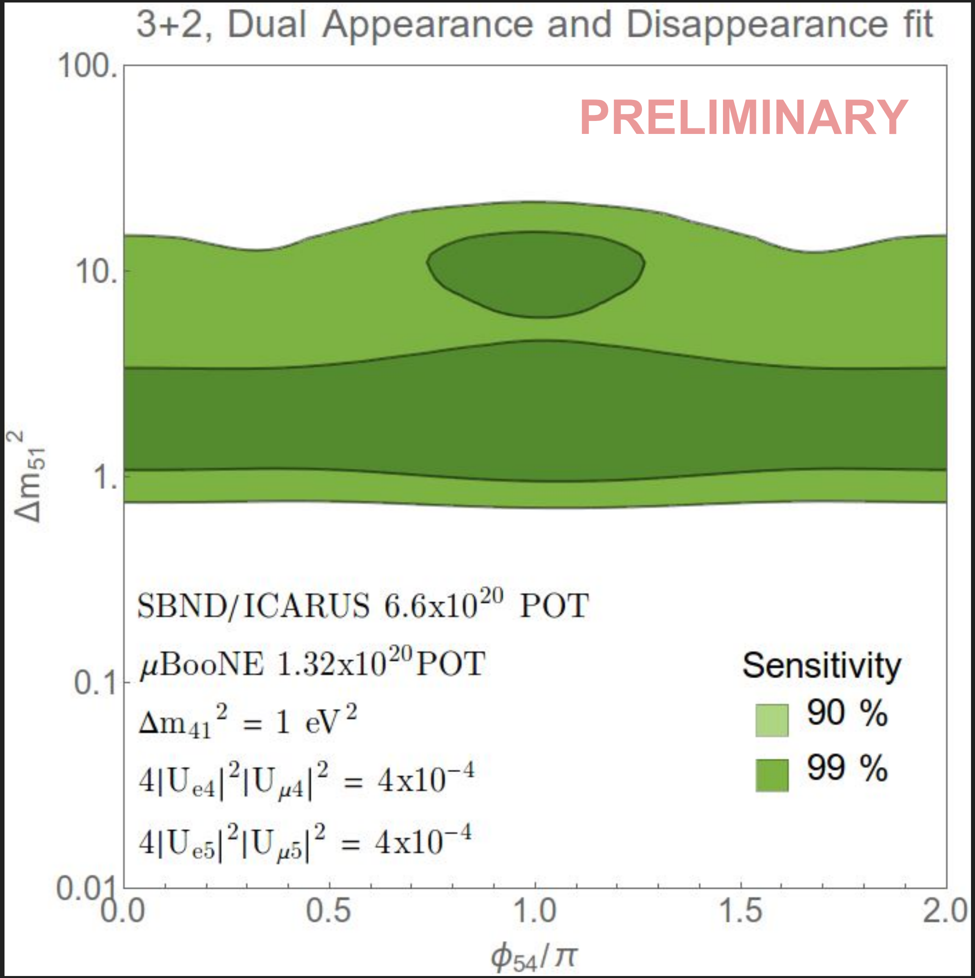


3+N Global Coverage

This is how much of the 99% globally allowed region SBN will be able to probe sensitively.

The vertical lines represent the 90% and 99% confidence cuts for the corresponding degrees of freedom for each 3+N curve.





CP Violation Sensitivity

Here, several oscillation parameters are fixed, but Δm^2_{51} and the CP violating phase ϕ are varied across their parameter spaces.

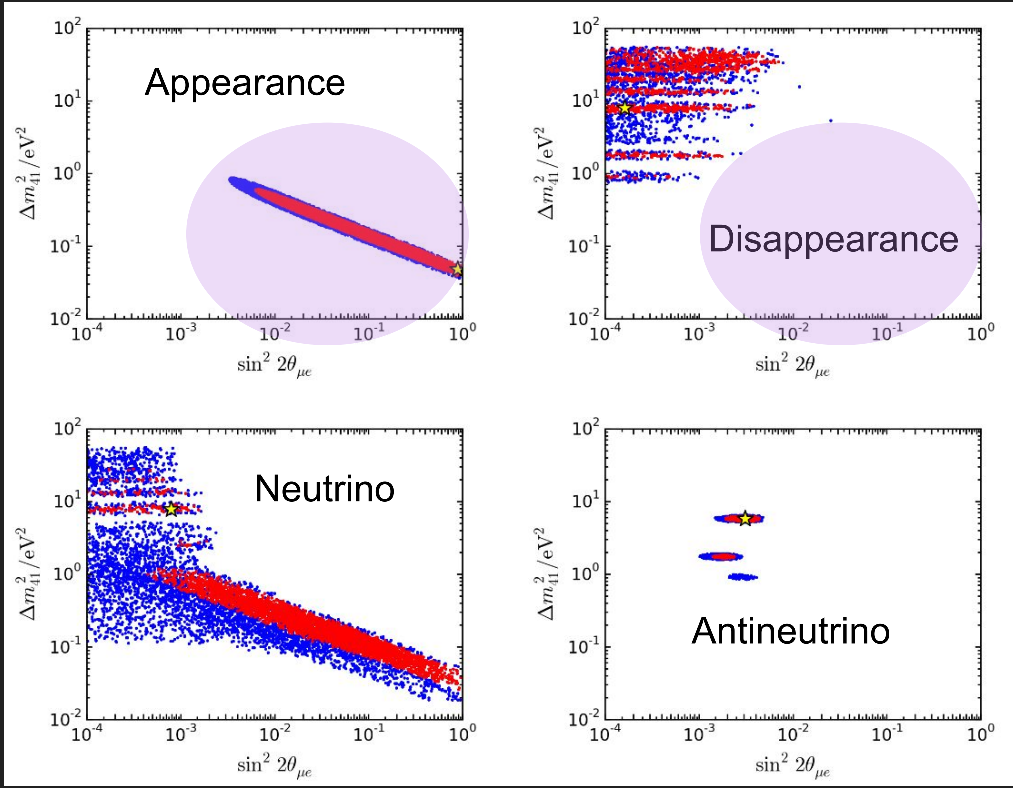
SBN will have some sensitivity to CP violation in some regions of parameter space!

Conclusions and things in progress

- Understanding sterile neutrinos is an incredibly high priority.
- SBN will be VERY good at probing current globally allowed regions for 3+1, 3+2 and 3+3 to high significance. More plots to show exactly how good are in progress!
- SBN is sensitive to CP violation in some areas of phase space and the extent of this will be explored further.
- Adding antineutrino mode running to the sensitivities is in progress.

Thanks.

backup



3+1 Global Fit

We can see some stark disagreement between the appearance and disappearance channels as well as between the neutrino and antineutrino channels.

This isn't great, so let's try adding another sterile.

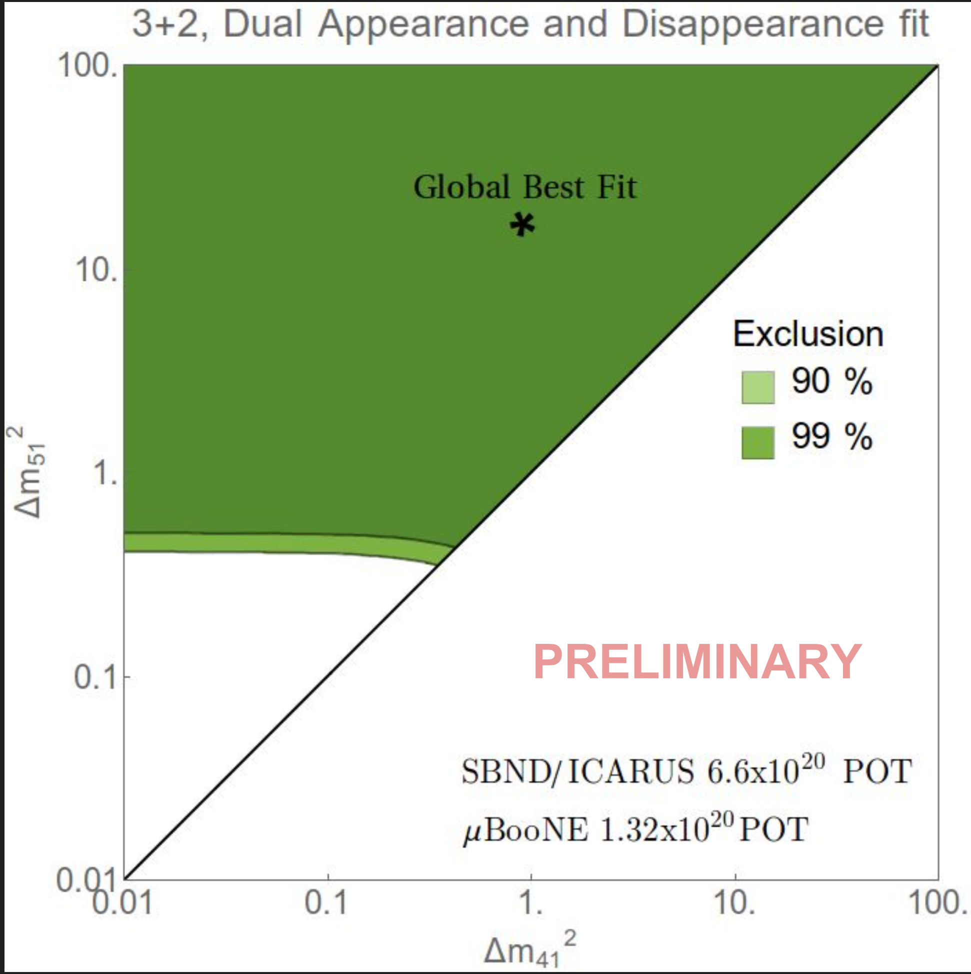
	χ^2(dof)	PG
App:	87.8 (87)	12%
Dis:	128.2 (147)	28%
App vs Dis:		.013%

Conrad et al, arXiv:1602.00671 [hep-ph]

3+2 Best Fit Sensitivity

Here, the mixing matrix elements and CPV phase are **fixed** to the best fit values of a recent global fit paper* while the mass splittings are allowed to vary over the space.

The global best fit point is marked by an asterisk and is firmly in the excluded region.

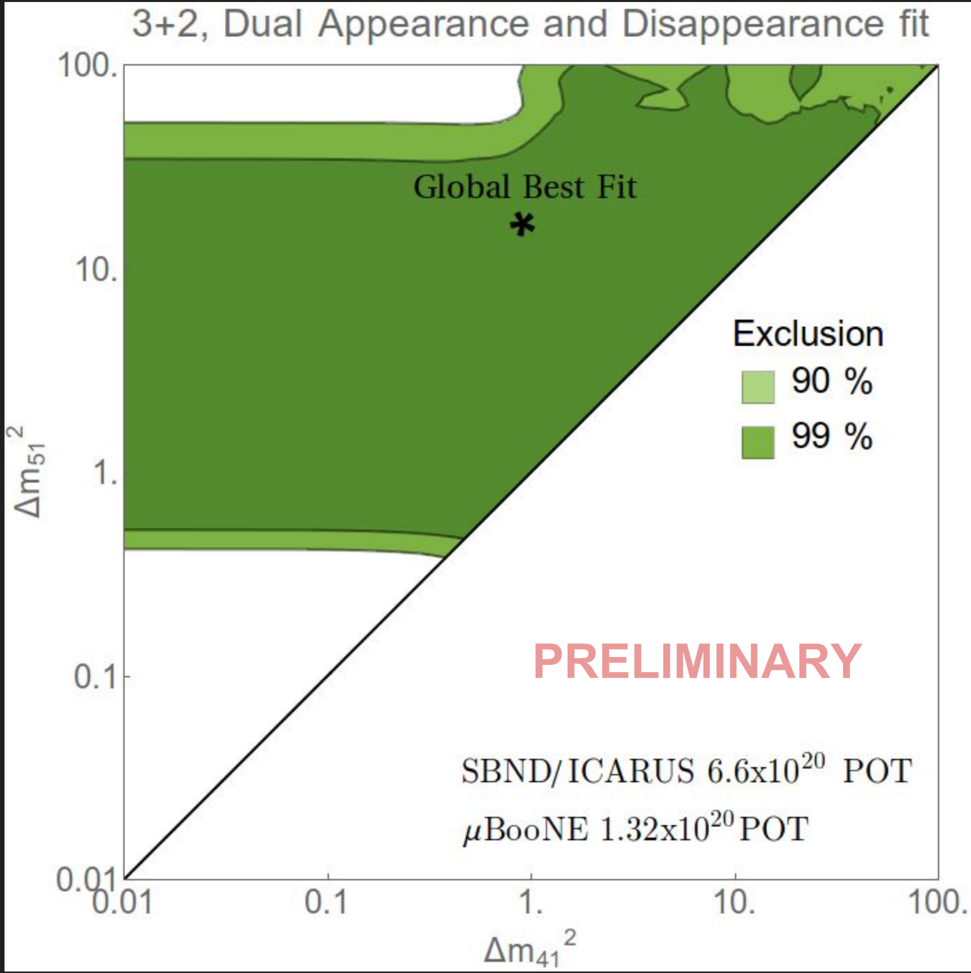


*:Adv.High Energy Phys. 2013 (2013) 163897

3+2 Best Fit Sensitivity with CP Variation

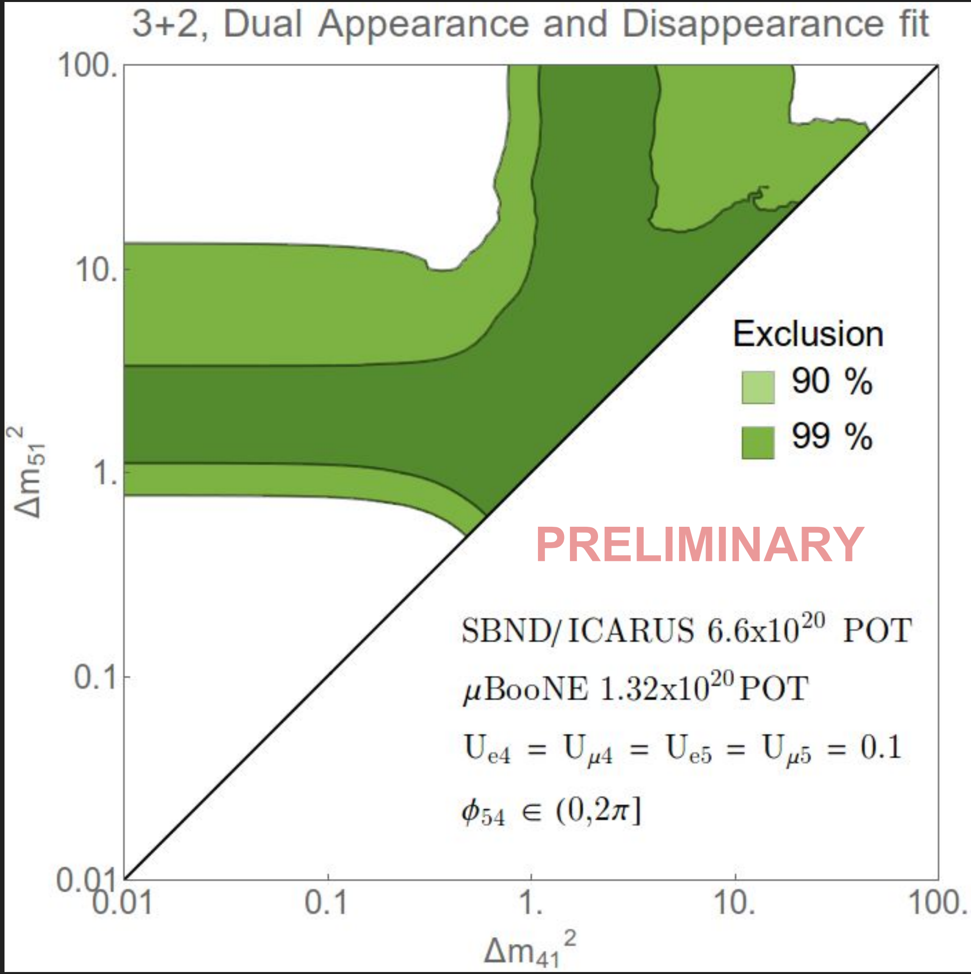
Now instead of fixing everything the CP violating phase is varied from 0 to 2π.

Regions that were previously excluded are now not! So SBN will have at least some sensitivity to CPV.

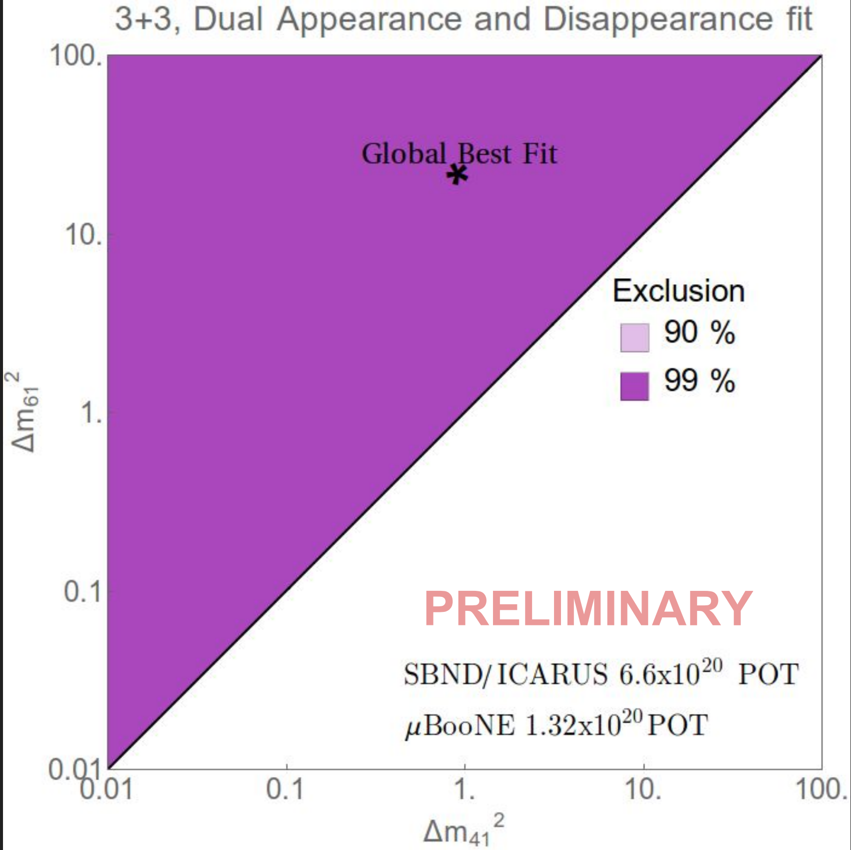


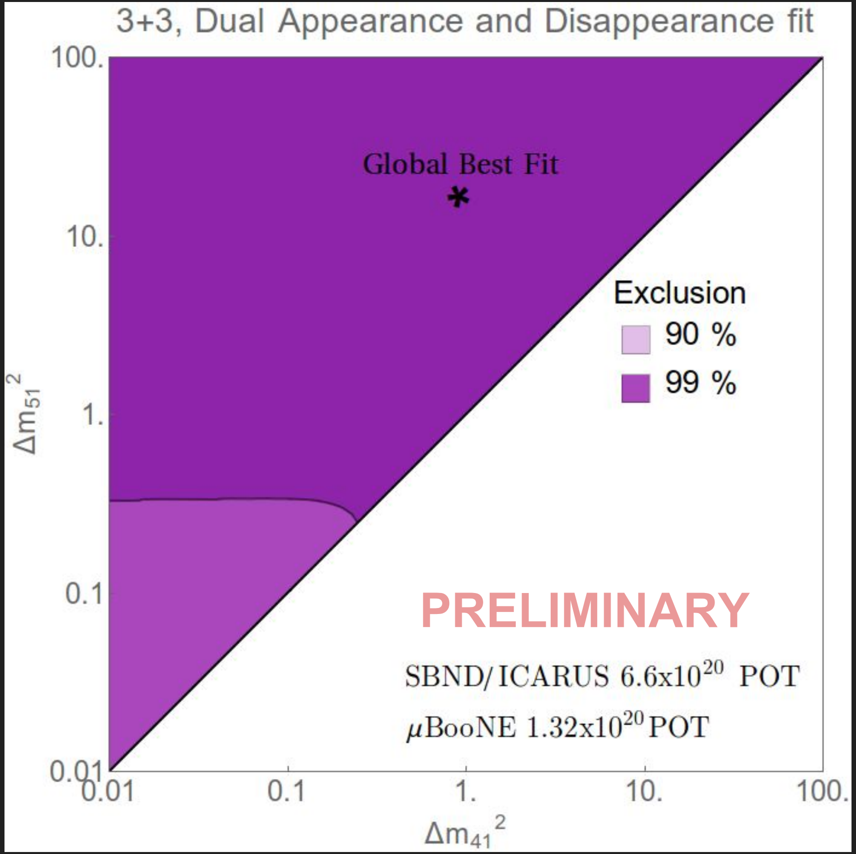
3+2 Sensitivity with CP Variation

Instead of taking the best fit point, the same plot is made by instead fixing the mixing matrix elements to be equal at some value.



3+3 Best Fit Sensitivity





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